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Our main accomplishment this past year has been to finalize and apply two approaches to output feedback adaptive control. The first is a direct adaptive approach, while the second uses a new error state observe. Both approaches overcome the limitation of earlier adaptive state observer based methods, which require that the order of the plant be known, and impose severe restrictions on the relative degree of regulated output variables. Within this context, we also have continued to exploi our approach for adaptive 'hedging' of actuator limits, which was the highlight of last year's report. We have also made some progress in the area of decentralized adaptive control. Our most significant interactions have been with NASA Marshall, NASA Ames, Wright Patterson AFB, Eglin AFB, Boeing and Lockheed.

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NEURAL NETWORK BASED ADAPTIVE CONTROL OF UNCERTAIN AND UNKNOWN NONLINEAR SYSTEMS

Final Report

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1 September, 2001

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NEURAL NETWORK BASED ADAPTIVE CONTROL OF UNCERTAIN AND UNKNOWN NONLINEAR SYSTEMS

GRANT NUMBER: F49620-01-1-0024

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Objectives

The objectives of this research effort are to exploit recent advances in neural network (NN) based adaptive control targeted to treat a very general class of nonlinear system, for which the dynamics are not only uncertain, but may be unknown except for minimal structural information, such as the relative degree of the regulated output variables. We are particularly interested in designing adaptive control systems that are robust with respect to both parametric uncertainty and unmodeled dynamics. Extensions to decentralized control are also of interest. In addition, we place a high priority on transition opportunities in aircraft flight control, control of flows, control of flexible space structures, and control of aeroelastic wings.

Status of Effort

Our main accomplishment this past year has been to finalize and apply two approaches to output feedback adaptive control. The first is a direct adaptive approach, while the second uses a new error state observe. Both approaches overcome the limitation of earlier adaptive state observer based methods, which require that the order of the plant be known, and impose severe restrictions on the relative degree of regulated output variables. Within this context, we also have continued to exploit our approach for adaptive 'hedging' of actuator limits, which was the highlight of last year's report. We have also made some progrėss in the area of decentralized adaptive control. Our most significant interactions have been with NASA Marshall, NASA Ames, Wright Patterson AFB, Eglin AFB, Boeing and Lockheed.

Accomplishments

Adaptive Output Feedback Control,[J2,J3,J4,S1,S2,S4,C6,C10]: Output feedback control architectures typically make use of state estimation, and therefore require that the dimension of the plant be known. Existing approaches either restrict the output to have full relative degree, or restrict the uncertainties in the plant to be dependent only on the output variables. Development of an adaptive output feedback approach for highly uncertain systems that overcomes these restrictions has been the main thrust of our research during the past several years. Our efforts this year have resulted in two promising approaches [J3, S1]. The first is a *direct* adaptive control approach. The second uses a novel, non-adaptive error state observer. The controller architectures have proven not only to be robust to unmodeled dynamics, but also have the capability to interact with and control these dynamics. The control architecture for the first approach is shown in Figure 1. The main features of this architecture include the dynamic compensator, with an additional output $(\tilde{y}_{ad})$ used in the NN training algorithm, and a delayed signal generation block, the outputs of which are used as inputs to the NN and are utilized to estimate the model inversion error from past measurements.

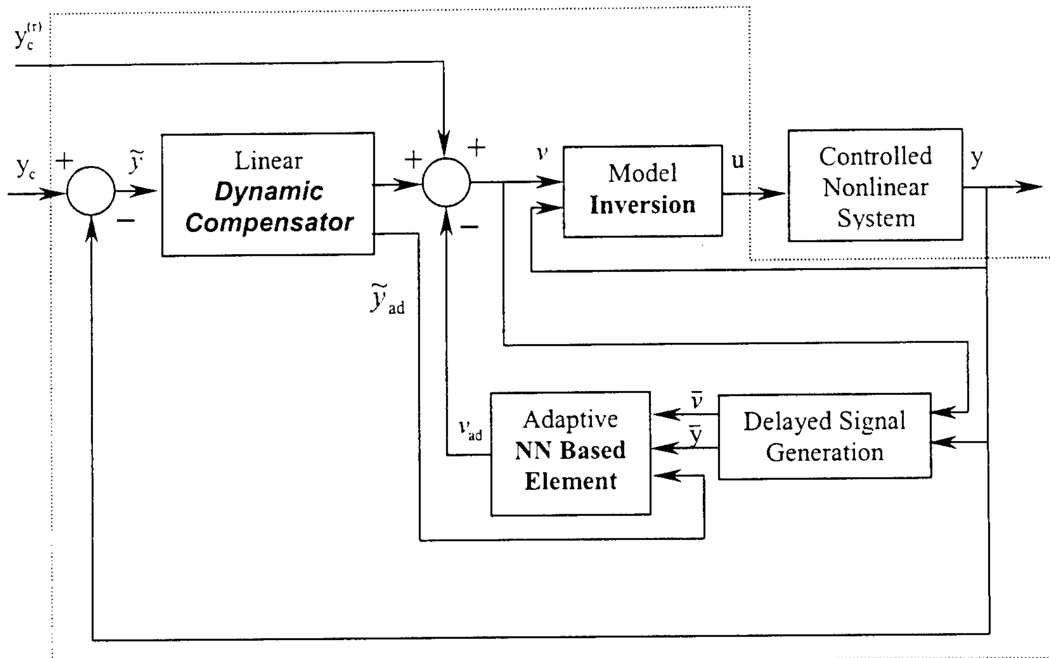


Fig. 1 The adaptive output feedback control architecture.

The delayed signal generation block is common to both approaches. We have considered general SISO systems represented by the system equations

$$\dot{x} = f(x,u)$$
$$y = h(x)$$

where $x \in R^n$ is the system state vector, u is the scalar control input, y is the scalar measurement and regulated output, and $f(\cdot,\cdot)$ and $h(\cdot)$ are partially known, or unknown sufficiently smooth functions. Additional outputs, which are not regulated, may be incorporated into the design approach. The only modeling assumption is that the relative degree $(r \le n)$ of the output is known. Thus, the r^{th} derivative of the output is the first derivative of the output that is "strongly" affected by the control, i.e.

$$y^{(r)} = h_r(x,u)$$

where $h_r(x,u)$ is also a partially known, or an unknown function. Feedback linearization is performed by introducing the transformation

$$v = \hat{h}_r(y,u)$$

where $\hat{h}_r(y,u)$ is the best available *invertible* approximation of $h_r(x,u)$, and v is commonly referred to as pseudo-control. Since only the measured signal can be used for control, a dynamic compensator is introduced to stabilize the linear portion of the tracking error dynamics, and the NN operates only on the available input/output data. Under the assumption that the plant is observable, we have shown that the unknown model inversion error can be mapped from present and past input/output data [S2]. The delayed signal generation block of Fig.1 provides the inputs required for this function.

One of the immediate advantages of our result is that the dimension of the plant (dimension of the state vector x) is not needed in the design, and the only information required is the relative degree of the measured signal. Thus, the result is applicable to plants having both parametric uncertainty and unstructured unmodeled dynamics.

<u>*Example:*</u> Consider a two-degree of freedom system

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= -2(x_1^2 - 1)x_2 - x_1 + u \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= -x_3 - 0.2x_4 + x_1
\end{aligned}$$

with regulated output given by

$$y = x_1 + x_2$$

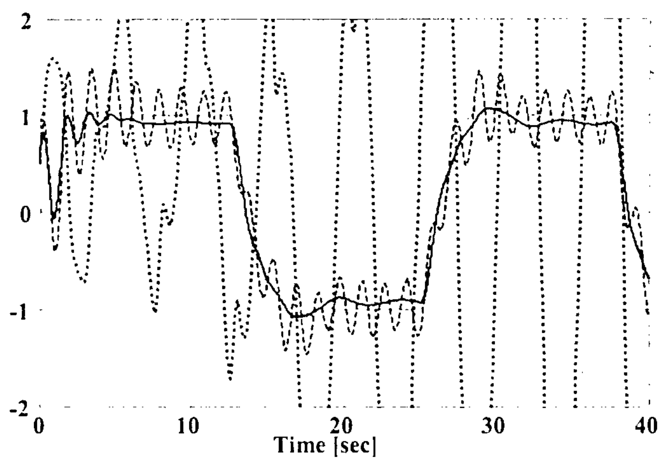


Figure 2. Responses With Unmodeled Dynamics

The output y has a relative degree of two. The system can be thought of as a nonlinear single degree of freedom rigid body (x_1 and x_2 states) coupled to a lightly damped unmodeled mode. The unmodeled mode is excited by the rigid body dynamics and is coupled to the output. Ideally we wish to regulate only x_1, and not the measurement y. The low natural frequency of the unmodeled mode is encompassed by the bandwidth of the control design. Moreover, the inverting design is performed without knowledge of the nonlinearities in the rigid body mode. This presents a very difficult control design problem. Figure 2 shows the x_1 state responses with neural network adaptation gains of 0, 10 and 50, and compares these responses with the command filter output (smooth line). The response without adaptation (dotted line, adaptation gain = 0) is unstable, due to the unmodeled mode. The response progressively improves and approaches the command as the adaptation gain is increased. This demonstrates the ability of the output feedback approach to accommodate both parametric uncertainty (in the rigid body dynamics) and unmodeled dynamics (the added mode). An illustration is given in [C3] that addresses nonlinear modeling of the actuation process and the use of 'hedging' in the adaptive process, but for the case of state feedback. This has been extended to output feedback, but not yet published. An application to flight control currently undergoing flight testing is described in [S1,C10].

Decentralized Adaptive Control, [S3]: We have developed an adaptive decentralized state feedback control architecture for large-scale systems with interconnections being bounded linearly by their tracking error norms. The local subsystems are assumed to be feedback linearizable. Future research will investigate removing this last assumption, and possible extensions to the output feedback case.

Personnel Supported

Faculty:	Calise, A.J., Professor.
Visiting Scholars:	Hovakimyan, N., Ph.D. in Physics and Mathematics from the Moscow Institute of Applied Mathematics.
	Idan, M, Visiting Professor from the Technion, Israel Institute of Technology
Students:	Nardi, F., graduate research assistant
	Johnson, E., graduate research assistant
	Kutay, A., graduate research assistant

Interactions/Transitions

Conferences: ACC, AIAA GN&C, ASME FEDSM, CDC (see reference list)

Consultations: Technical meetings and presentations with Dr. Siva Banda, Mark Mears (WPAFB), Marc Steinberg (NASC), and Johnny Evers (Eglin AFB) in the area of Adaptive Guidance and Flight Control.

New Initiatives: Two new collaborative efforts funded by industry. Both will utilize our adaptive output feedback approach to deal with flexible dynamics in flight control applications.

Corporate Custormers: Raytheon and Lockheed

Technical POCs: Dr. Mike McFarland, 520-794-0592, mbmcfarland@west.raytheon.com
Jim Buffington, :817-935-1030, james.m.buffington@lmco.com

An STTR effort in developing biologically inspired guidance algorithms for guided munitions.

Government Customer: AFOSR and Eglin AFB

Techical POCs: Dr. Robert Cohn, 703-696-7722, robert.cohn@afosr.af.mil
Johnny Evers, 850-882-2961 x3330, evers@eglin.af.mil

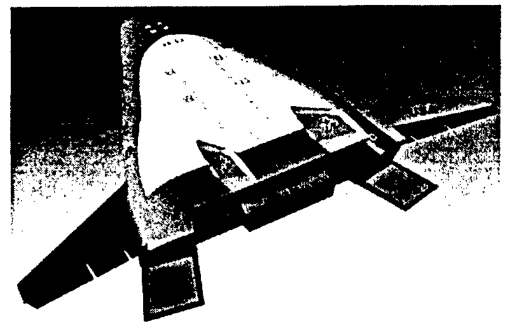
Corporate Customer: Guided Systems Technology

Technical POC: Dr. Eric Corban, 770-898-9100, corban@mindspring.com

Civil Transportation, [C5,C8]: A cooperative effort with NASA Ames in the area of flight safety. During this past year we participated in a series of piloted simulations at the moving base simulation facility. We have extended our approach from a propulsion only mode, to one that can use all available operating surfaces, and which can be integrated with an existing flight control system. This was accomplished by a novel implementation of our output feedback adaptive approach in conjunction with pseudo-control hedging to accommodate the control limits that are encountered in these applications.

Government Customers: NASA Ames and NASA Langley

Technical POC: Joe Totah, 650-604-1864, Joseph_Totah@qmgate.arc.nasa.gov



Launch Vehicles, [C2,C4,C7]: We are working with NASA Marshall and lately with WPAFB to design integrated adaptive guidance and flight controls for future launch vehicles. Our approach has completely eliminated the need for gain tables. During this past year we have investigated an integrated guidance and flight control design that adapts to both force and moment perturbations due to failure. The approach adapts the ascent guidance solution to insure that the path that is commanded is flyable.

Government Customers: NASA Marshall and WPAFB
Technical POCs: Dr. John Hanson, 256-544-2239, john.hanson@msfc.nasa.gov
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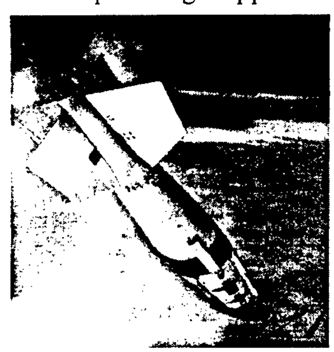
Corporate Custormers: Boeing and Lockheed
Technical POCs: Dr. Eugene Lavretsky, (562) 982-9269, eugene.lavretsky@boeing.com
Dr. Hussein Youssef, (661) 572-5780, hussein.youssef@lmco.com

Guided Munitions, [J1]: We have entered a Phase-III SBIR effort with Guided Systems Technologies. This work is aimed at demonstrating that a single tail kit with a fixed autopilot design can be used to control a wide class of guided munitions. Also, the autopilot design must accommodate changes in mission profiles, without significant redesign. The design should not require accurate aerodynamic data as well. This will further reduce costs by reducing the need for wind tunnel testing. During this past year we competed all Phase-II evaluations. We are currently providing preliminary studies and test planning support for a series of flight tests planned for later this

Government Customer: AFWL, Eglin AFB
POC: Johnny Evers, 850-882-2961 x3330, evers@eglin.af.mil
Corporate Customer: Boeing Phantom Works
POC: Kevin Holt, 636-925-5114, kevin.d.holt@boeing.com



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Patent Disclosures

Johnson, E.N., Calise, A.J., "Improvements to Adaptive Neural Networks Related to Input Constraints," June, 2000.
Calise, A.J, Hovakimyan, N., "Neural Network Based Adaptive Control of Nonlinear Systems with Unknown Dynamics Using Direct Output Feedback," June, 2000.

Honors/Awards

A. Calise:	Aviation Week Laurel Honoree for the year 2000 in recognition of a NN adaptive reconfigurable flight control demonstration on the X-36 aircraft.
E. Johnson:	*Ph.D. in Aerospace Engineering, December, 2000* *Lockheed Martin Faculty Junior Chair in Avionics, January, 2001*
F. Nardi:	*Ph.D. in Aerospace Engineering, December, 2000*
A. Calise:	Best Paper for the 1998 AIAA GN&C Conference AIAA Fellow, 1993 AIAA Mechanics and Control of Flight Award, 1992

Publications http://www.ae.gatech.edu/research/controls/

J1. Calise, A.J., Sharma, M. and Corban, J.E. "Adaptive Autopilot Design for Guided Munitions," AIAA Journal of Guidance, Control, and Dynamics, Vol. 23, No. 5, 2000.

J2. Hovakimyan, N., Rysdyk, R. and Calise, A.J., "Dynamic Neural Networks for Output Feedback Control," International Journal of Robust and Nonlinear Control, Vol.11, No.1, 2001.

J3. Calise, A.J., Hovakimyan, N., and Idan, M., "Adaptive Output Feedback Control of Nonlinear Systems Using Neural Networks," Automatica, Vol.37, No.8, 2001.

J4. Hovakimyan, N., Nardi, F., Calise, A.J., Lee, H., "Adaptive Output Feedback Control of a Class of Nonlinear Systems using Neural Networks, Accepted Intnl. Journal of Control, 2001.

S1. Hovakimyan, N., Nardi, F., Kim, N. and Calise, A.J., "Adaptive Output Feedback Control of Uncertain Systems Using Single Hidden Layer Neural Networks, Submitted to IEEE Transactions on Neural Networks.

S2. Hovakimyan, N., Nardi, F. and Calise, A.J., "A Novel Observer Based Adaptive Output Feedback Approach for Control of Uncertain Plants. Submitted to IEEE Transactions on Automatic Control, 2001.

S3. Nardi, F., Hovakimyan, N., and Calise, A.J., "Decentralized Control of Large-Scale Systems Using Single Hidden Layer Neural Networks. Submitted to International Journal of Robust and Nonlinear Control, 2001.

S4. Hovakimyan, N., Calise, A.J., "Adaptive Output Feedback Control of Uncertain Multi-Input Multi-Output Systems Using Single Hidden Layer Neural Networks, Submitted to International Journal of Control, July, 2001.

C1. Nardi, F. Calise, A.J., "Robust Adaptive Nonlinear Control using Single Hidden Layer Neural Networks", Conference on Decision and Control, Sydney, Australia, December 2000.

C2. Johnson, E.N., Calise, A.J. and Corban, J.E., "Adaptive Guidance and Control for Autonomous Launch Vehicles, IEEE Aerospace Conference, Big Sky, MT, April 2001.

C3. Idan, M., Calise, A.J., Kutay, A.T., and Parekh, D.E., "Adaptive Neural Network Based Approach for Active Flow Control, ASME Fluids Engineering Division Summer Meeting, New Orleans, Louisiana, May 2001.

C4. Johnson, E.N., Calise, A.J., "Neural Network Adaptive Control of Systems with Input Saturation," American Control Conference, Arlington, Virginia, June 2001.

C5. Idan, M., Johnson, M.D. and Calise, A.J., "Intelligent Aerodynamic/Propulsion Flight Control For Flight Safety: A Nonlinear Adaptive Approach," American Control Conference, Arlington, Virginia, June 2001.

C6. Hovakimyan, N., Nardi, N. and Calise, A.J., "A Novel Observer Based Adaptive Output Feedback Approach for Control of Uncertain Systems," American Control Conference, Arlington, Virginia, June 2001.

C7. Johnson, E.N., Calise, A.J., "Reusable Launch Vehicle Adaptive Guidance and Control Using Neural Networks, AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.

C8. Idan, M., Johnson, M.D. and Calise, A.J., "A Hierarchical Approach to Adaptive Control fo Improved Flight Safety, AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.

C9. Sharma, M., Calise, A.J., "Neural Network Augmentation of Existing Linear Controllers, AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.

C10. Hovakimyan, N., Kim, N., Calise, A.J. and Prasad, J.V.R., "Adaptive Output Feedback for High Bandwidth Adaptive Control of an Unmanned Helicopter," AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.